An update of the DIRAC result on the pion-pion $|a_0-a_2|$ scattering length

DImeson **R**elativistic **A**tomic **C**omplex

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16 Institutes

Spokesman: Leonid Nemenov, Dubna

Outline

Present status of $\pi\pi$ scattering length
Short presentation of the DIRAC Method
The experiment
Reminder of published result
Various improvements
Present sensitivity with existing data
Outlook

$\pi\pi$ scattering lengths, present situation (Nemenov, Trento, June 2006)

Present low energy QCD predictions: $\boldsymbol{a_0 = 0.220 \pm 0.005\,(2.3\%)}$ $\boldsymbol{a_2 = -0.0444 \pm 0.0010\,(2.3\%)}$

(Colangelo, Gasser,Leutwyler, Nucl.Phys B603(2001)125)

$\boldsymbol{a_0 - a_2 = 0.265 \pm 0.004\,(1.5\%)}$

K_{e4} First result (L. Rosselet *et al.,* Phys. Rev. D15 (**1977**) 574)**:** $a_0 = 0.28 \pm 0.05(18\%)$ using Roy eqs

K_{e4} E865/BNL (S.Pislak *et al.*, Phys. Rev. Lett. 87 (**2001**) 221801) **:** $K \to \pi^+\pi^- e^+ \nu_e$

using Roy eqs.

$a_0 = 0.203 \pm 0.033(16\%)$

$a_2 = -0.055 \pm 0.023(42\%)$

using Roy eqs. and ChPT constraints $a_2 = f_{ChPT}(a_0)$

$a_0 = 0.216 \pm 0.013\ (stat) \pm 0.004(syst) \pm 0.002\ (theor)$

$\pm 6\%\ (stat)\quad \pm 2\%(syst)\quad \pm 1\%\ (theor)$

$K^+ \to \pi^0\pi^0\pi^+$ NA48/2 (J.R.Batley et al., Phys. Lett. B633 (2006) 173)**:**

$(a_0 - a_2)m_\pi = 0.268 \pm 0.010\,(stat) \pm 0.004\,(syst) \pm 0.013(ext)$

$\pm 3.7\%(stat)\quad \pm 1.5\%(syst)\quad \pm 4.9\%(ext)$

DIRAC, 2001data (Phys. Lett. B 619 (2005) 50)

$$(a_0 - a_2)m_\pi = 0.264 \begin{array}{l} +\ 0.033\ (12.5\%) \\ -\ 0.020\ (7.6\%) \end{array} (tot)$$

DIRAC improved, 2001–2002 data

$$\delta(a_0 - a_2) = \pm 3.6\%\,(stat) \begin{array}{l} +6.6\% \\ -2.1\% \end{array} (syst) = \begin{array}{l} +7.4\% \\ -4.2\% \end{array} (tot)$$

Upgraded DIRAC (DIRAC II)

$$\delta(a_0 - a_2) = \pm 2\%(stat) \pm 1\%(syst) \pm 1\%(theor)$$

ππ scattering length from DIRAC

Method: **Measure lifetime of the $\pi^+\pi^-$ atom (of order 10^{-15} s)**

Lifetime of $\pi^+\pi^-$ atom due to decay : strong $\pi^+\pi^- \to \pi^0\pi^0$ (99.6%)

el. magn. $\pi^+\pi^- \to \gamma\gamma$ (0.4%)

Lifetime linked to S-wave $\pi^+\pi^-$ scattering lengths (a_2-a_0)

$$\Gamma_{1S}^{\pi^0\pi^0} = \frac{2}{9}\alpha^3 p_{\pi^0}^{c.m.} \left|a_0 - a_2\right|^2 (1+\delta)$$

$\alpha = 1/137.035999$

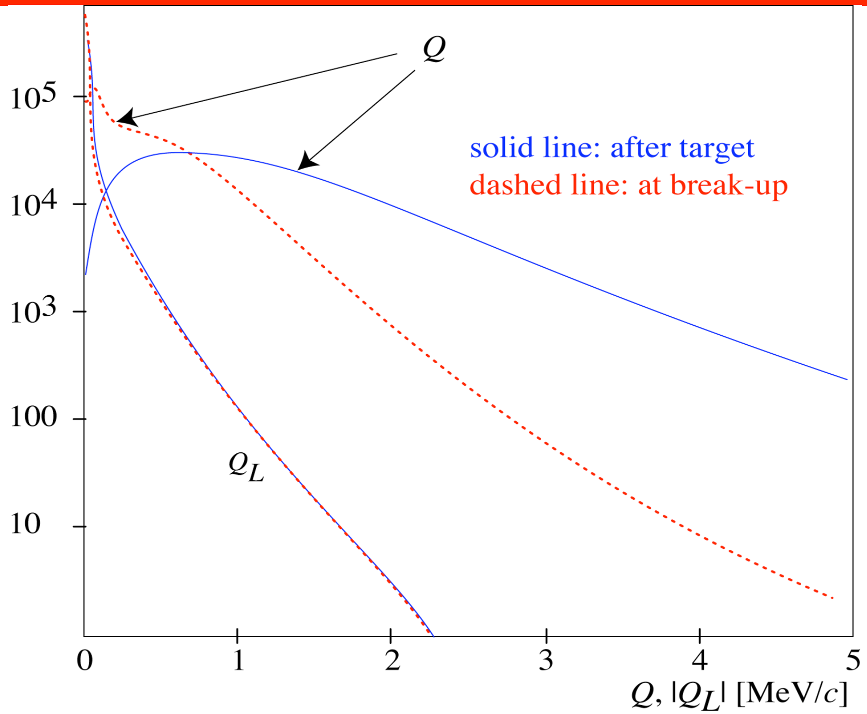
$p_{\pi^0}^{c.m.} = 35.50906\ [MeV]$

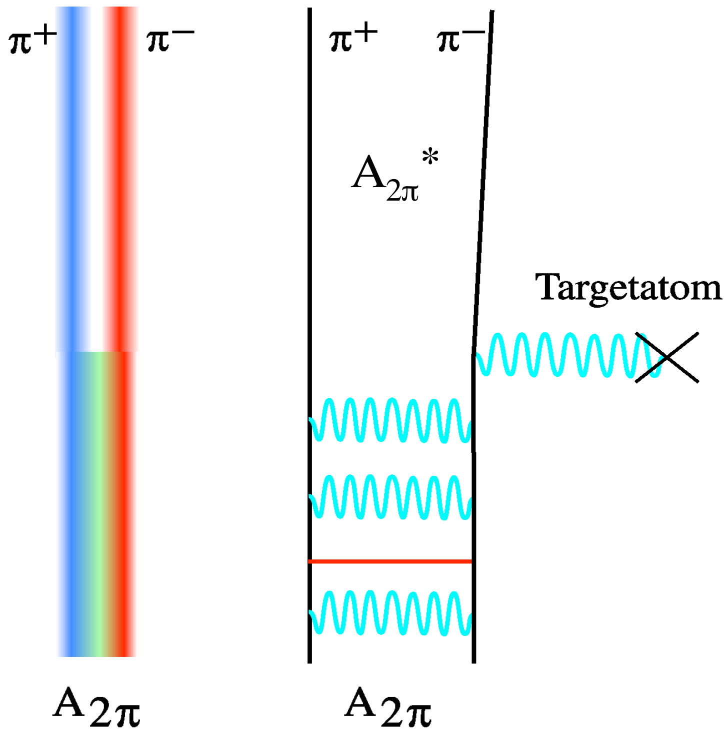
$\delta = (5.8 \pm 1.2)10^{-2}$

Atoms, excitation and break-up

Atoms are produced in $p_{(24\ GeV/c)}$-nucleus collisions (γ≈17).
In collisions, atom (binding energy 1.7keV) becomes excited or breaks up.

Pions from break-up (soft transverse kick) have very similar momenta and very small opening angle (small *Q*)





At target exit Q_T is smeared by multiple scattering.

Principle of measuring the lifetime

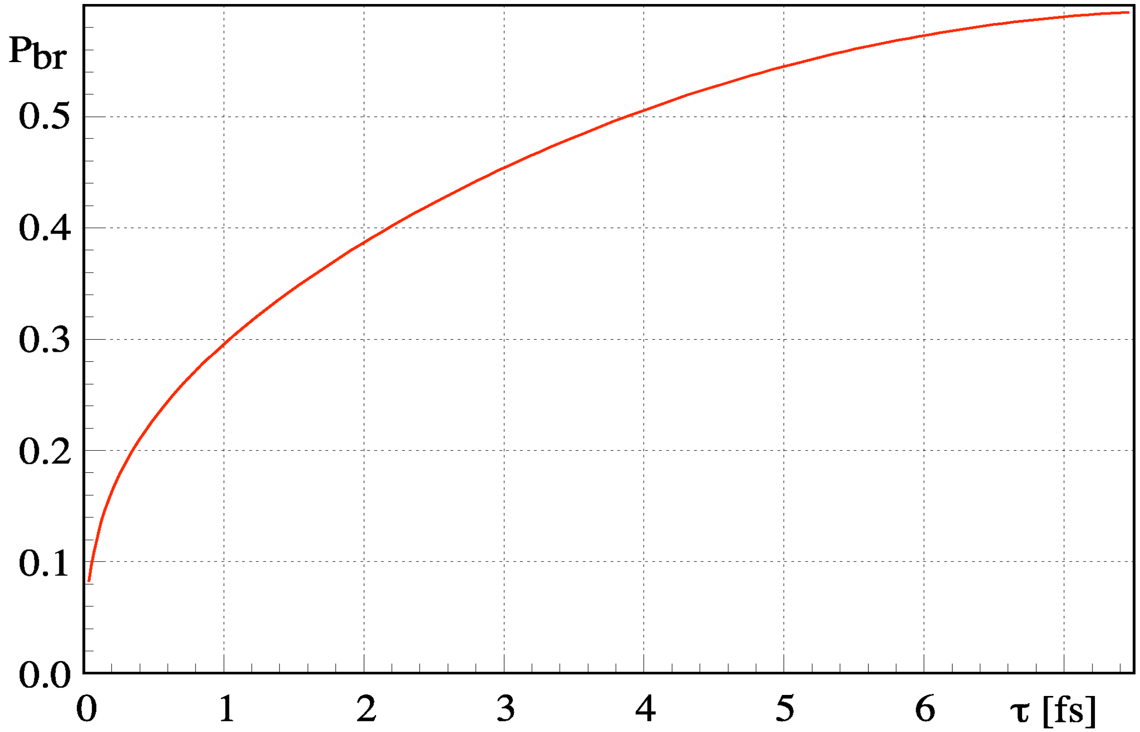
Excitation and break-up of produced atoms (N_A) are competing with decay

$\Rightarrow$Break-up probability P_{br} is linked to the lifetime

$\pi^+\pi^-$ pairs from break-up provide measurable signal n_A

P_{br} is linked to n_A :

$$P_{br} = n_A/N_A$$

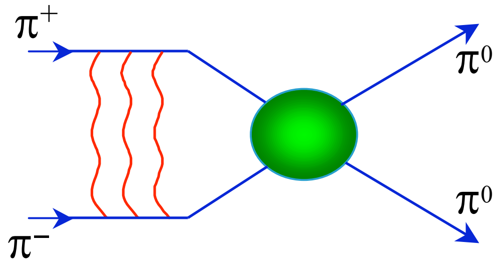


The number of produced atoms N_A is not directly measurable

Theoretical limitations ($A_{\pi\pi}$) (Nemenov, Trento, June 2006)

1. $A_{2\pi}$ lifetime

$$\Gamma(\pi^0\pi^0) = R_\pi (a_0 - a_2)^2 (1 + \delta_\pi)$$



H. Jalloul, H.Sazdjian 1998

M.A. Ivanov et al. 1998

A. Gashi et al. 2002

J. Gasser et al. 2001 → $\delta_\pi = (5.8 \pm 1.2) \cdot 10^{-2}$

Current accuracy from the $A_{2\pi}$ lifetime calculation $\frac{\Delta |a_0 - a_2|}{|a_0 - a_2|} = 0.6\%$

2. $A_{2\pi}$ interaction with matter (break-up)

L.Afanasyev, G.Baur, T.Heim, K.Hencken, Z.Halabuka, A.Kotsinyan, S.Mrowczynski, C.Santamarina, M.Schumann, A.Tarasov, D.Trautmann, O.Voskresenskaya
from Basel, JINR and CERN

Current accuracy from break-up probability P_{br} $\frac{\Delta |a_0 - a_2|}{|a_0 - a_2|} = 1.2\%$

To be reduced by factor 2

Background

Pairs of pions produced in high energy proton nucleus collisions are **coherent**,

- if they originate directly from hadronisation or
- involve short lived intermediate resonances.

Coherent pairs undergo Coulomb final state interaction and become "**Coulomb-correlated" (CC-background)**. In the limit of very low Q, Coulomb correlation may lead to **atomic bound states.**

This links the number of produced atoms N_A to the observable CC-background.

$$\frac{N_A}{N_{CC}} = \frac{\sigma_A^{tot}}{\sigma_{CC}^{tot}\Big|_{q \le q_0 = 2\,MeV/c}} = k_{th} = 0.615$$

Pairs of pions are **incoherent**,

- if one of them originates from long lived intermediate resonances, e.g. η's (**non-correlated**)
- because they originate from different proton collisions (**accidentals**)

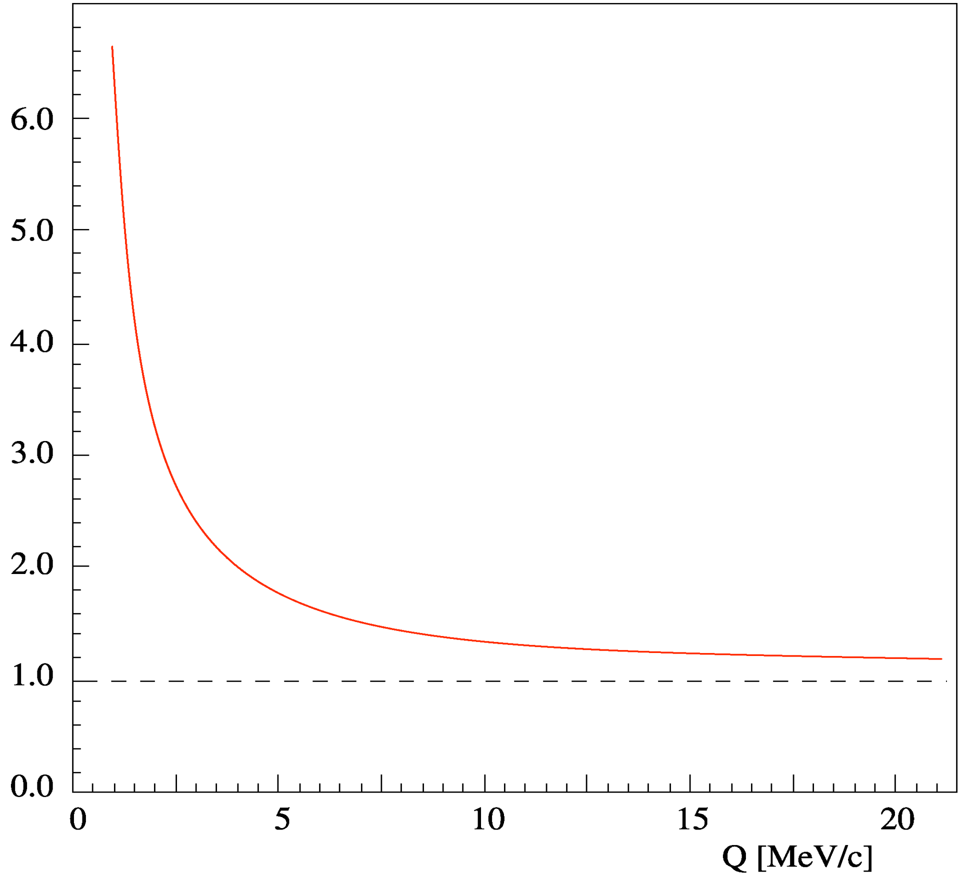
Coulomb Correlation

Coulomb-correlation leads to enhancement of low-Q event rate with respect to non-correlated events.

Coulomb enhancement function
(Sommerfeld, Gamov, Sacharov):

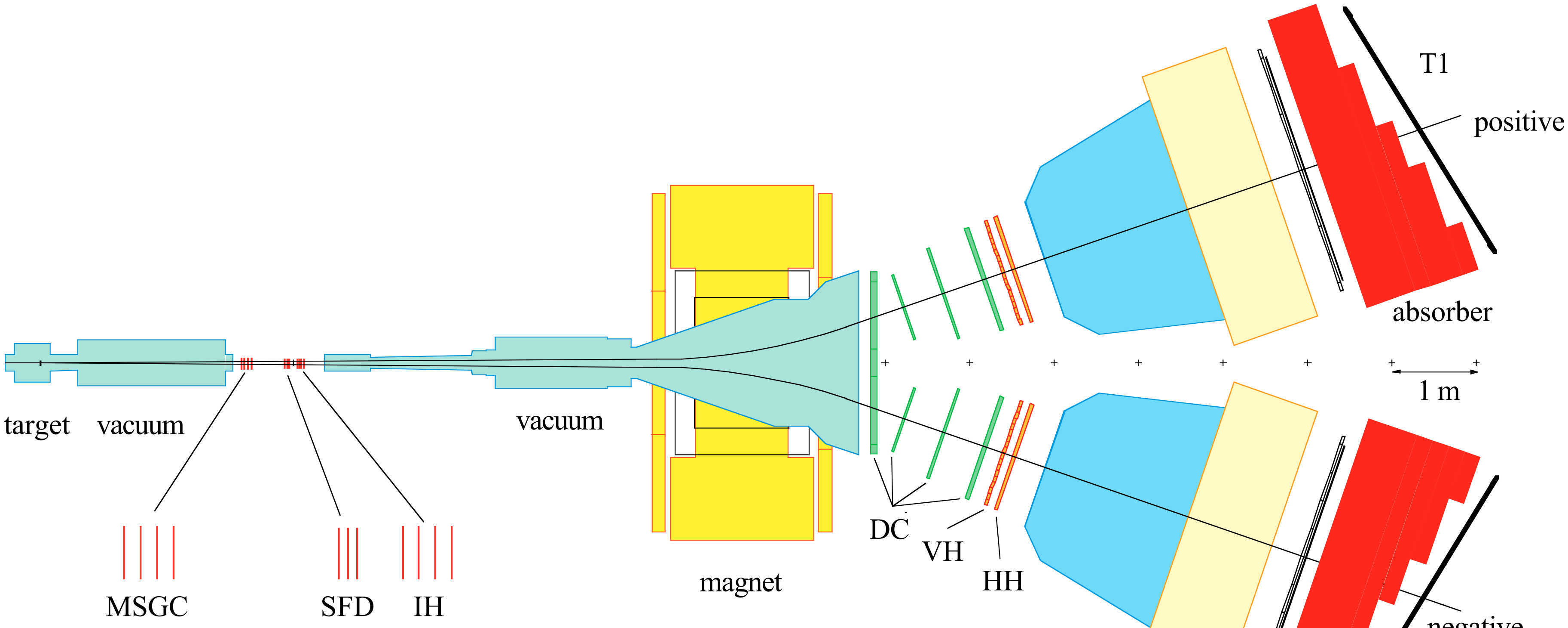
$$f_{CC}\left(Q\right) = \frac{2\pi\alpha m_{\pi^{\pm}} / Q}{1 - \exp\left(-2\pi\alpha m_{\pi^{\pm}} / Q\right)}$$

This enhancement function is valid for point-like production of the pion pair.



In reality, the production happens in a volume of finite size, which leads to a modification of the correlation function

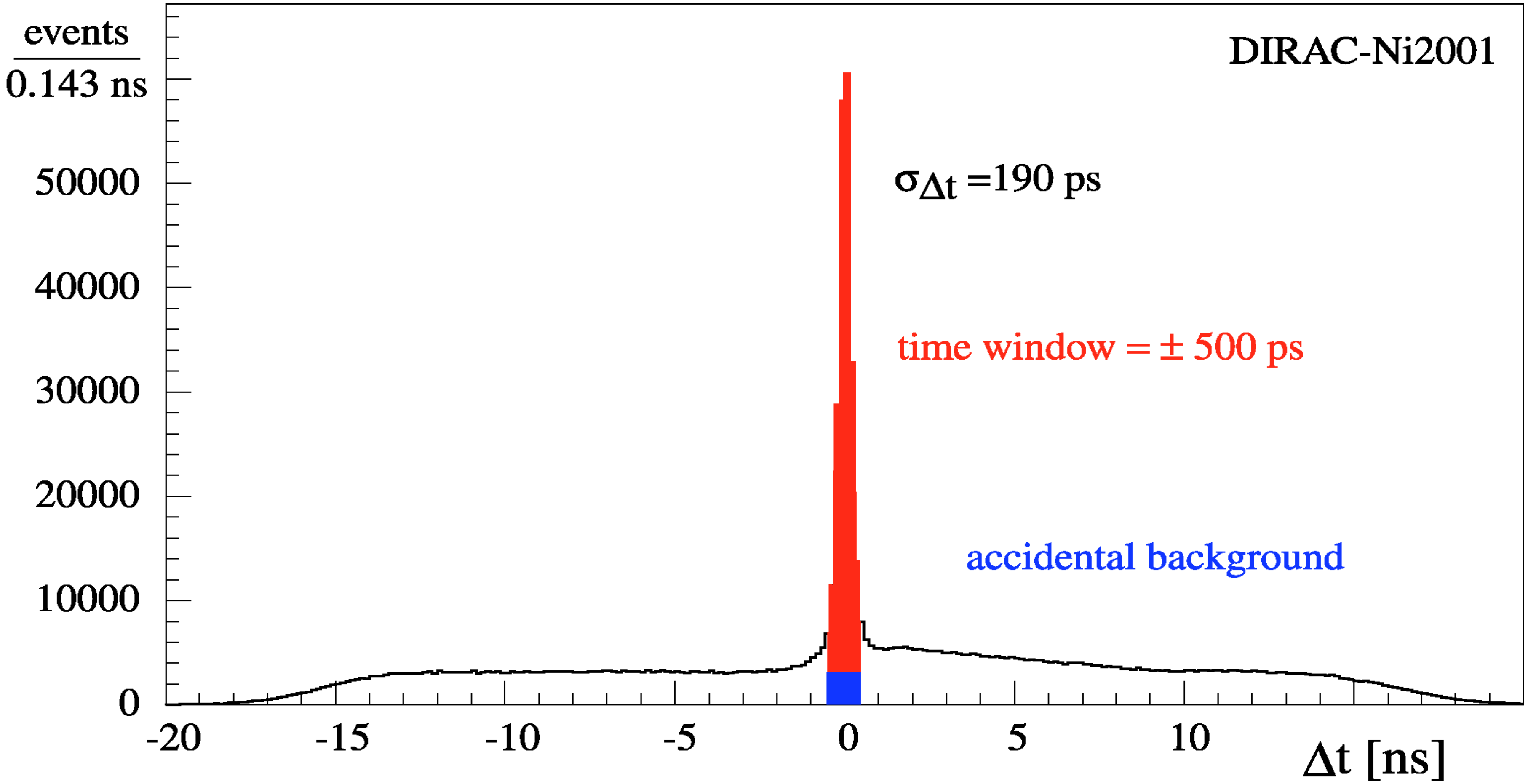
DIRAC spectrometer



MSGC: multi strip gas chambers
SFD: scintillation fiber detector
IH: scintillation dE/dx counters
magnet: 1.65 T, 2.2 Tm

DC: high resolution drift chambers
VH, HH: scintillation hodoscopes
C: Cherenkov counters
PSh: preshower detector
Mu: muon counters

Timing



events
0.143 ns
DIRAC-Ni2001
50000
40000
30000
20000
10000
0
$\sigma_{\Delta t}$ =190 ps
time window = ± 500 ps
accidental background
-20
-15
-10
-5
0
5
10
Δt [ns]

Monte-Carlo

Generators: tailored to the experiment (constant strong matrix elements).

1. **Accidental background** according to $\partial N_{acc}/\partial Q \propto Q^2$ (phase space) with momentum distributions as measured with accidentals
2. **Non-correlated background** according to $\partial N_{nC}/\partial Q \propto Q^2$ with momentum distribution as measured for one pion and Fritjof momentum distribution for long-lived resonances for second pion
3. **Coulomb-correlated background** according to $\partial N_C/\partial Q \propto f_{CC}(Q)*Q^2$ with momentum distribution as measured but corrected for long-lived incoherent pion pairs (Fritjof)
4. **Atomic pairs** according to dynamics of atom-target collisions and atom momentum

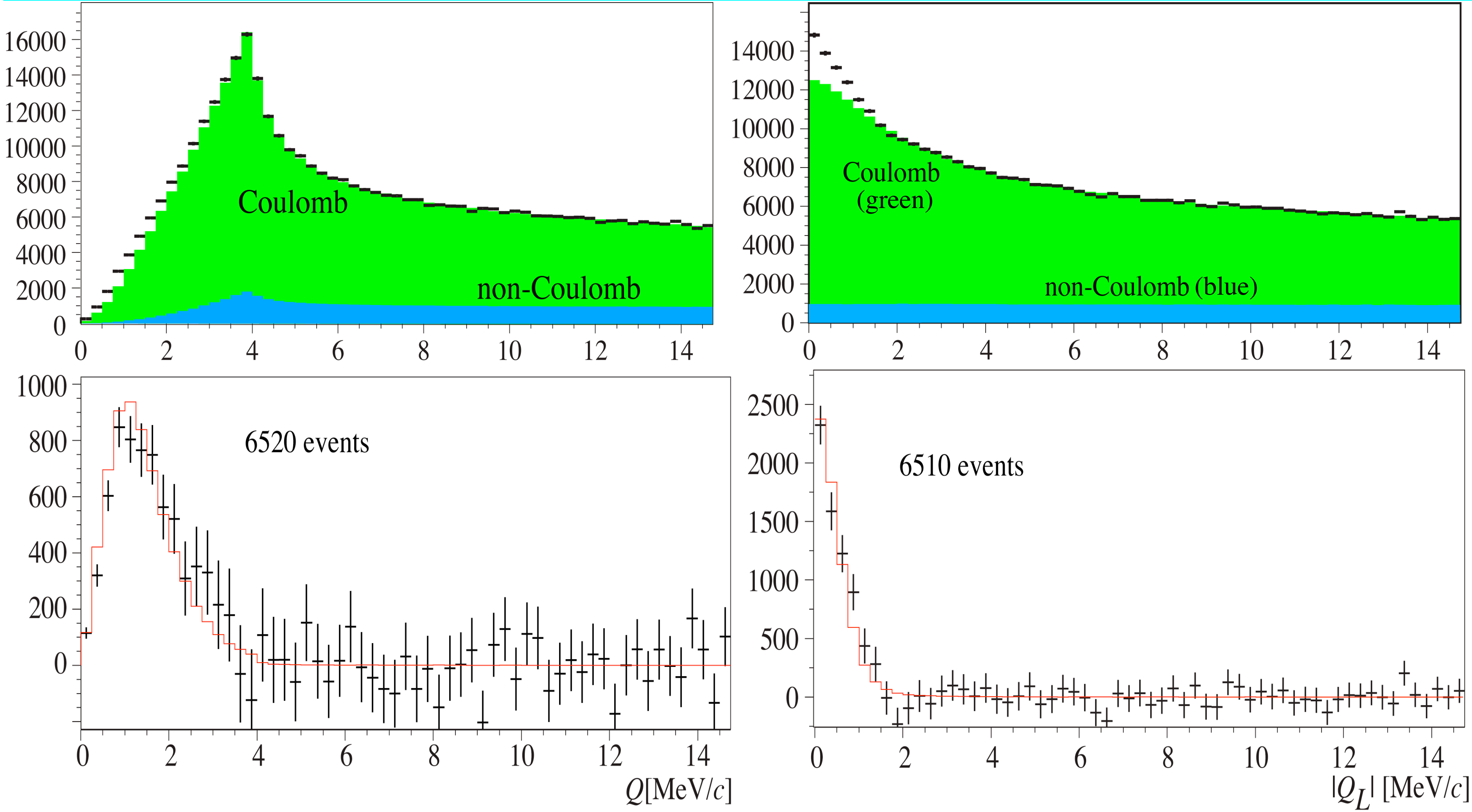
Geant4: full spectrometer simulation

Detector simulation: full simulation of response, read-out, digitalization and noise

Trigger simulation: full simulation of trigger processors

Reconstruction: as for real data

Experimental Q and Q_L distributions (Ni2001)



Published

Published (PLB 619, 2005, 50-60)

$$P_{br} = 0.452 \pm 5.1\%_{stat} \left(^{+1.99\%}_{-7.1\%}\right)_{syst}$$

Errors

Stat	± 0.023 (± 5.1%)		
Syst	CC-background	± 0.007(±1.6%)	
	Signal shape	± 0.002(±0.4%)	
	Multiple scattering	+ 0.006(+1.3%)	- 0.013(-2.9%)
	K^+K^-, pp_{bar}	+ 0.000(+0.0%)	- 0.023(-5.1%)
	Finite size	+ 0.000(+0.0%)	- 0.017(-3.8%)

Improvements due to reconstruction

Because of known difficulties in reconstructing the signal in Q_T (connected to uncertainties in multiple scattering) the earlier analysis was made in Q_L with a constraint on Q.

As a result of a dedicated measurement on multiple scattering, Q_T reconstruction is now much better and provides an independent determination of P_{br}, which can be averaged with the one from Q_L.

New fitting procedures in Q_L and Q_T (projections or 2D) produce smaller statistical error:

Published error on P_{br} from 2001 data: $N_{atoms} = 6530 \pm 294$ **new: $\approx \pm 220$**

Improved stat. error from 2001 data on P_{br} : ± 0.016 ($\pm 3.4\%$)

Improvements due to statistics

In addition to data from 2001 also data from 2002 (2D fits).

2001:	$N_{atoms} \approx 6500 \pm 220 (\pm 3.4\%)$
2002, 20 GeV:	$N_{atoms} \approx 4300 \pm 200 (\pm 4.6\%)$
2002, 24 GeV:	$N_{atoms} \approx 5500 \pm 300 (\pm 5.5\%)$
Total:	$\mathbf{N_{atoms} \approx 16000 \pm 420 (\pm 2.6\%)}$

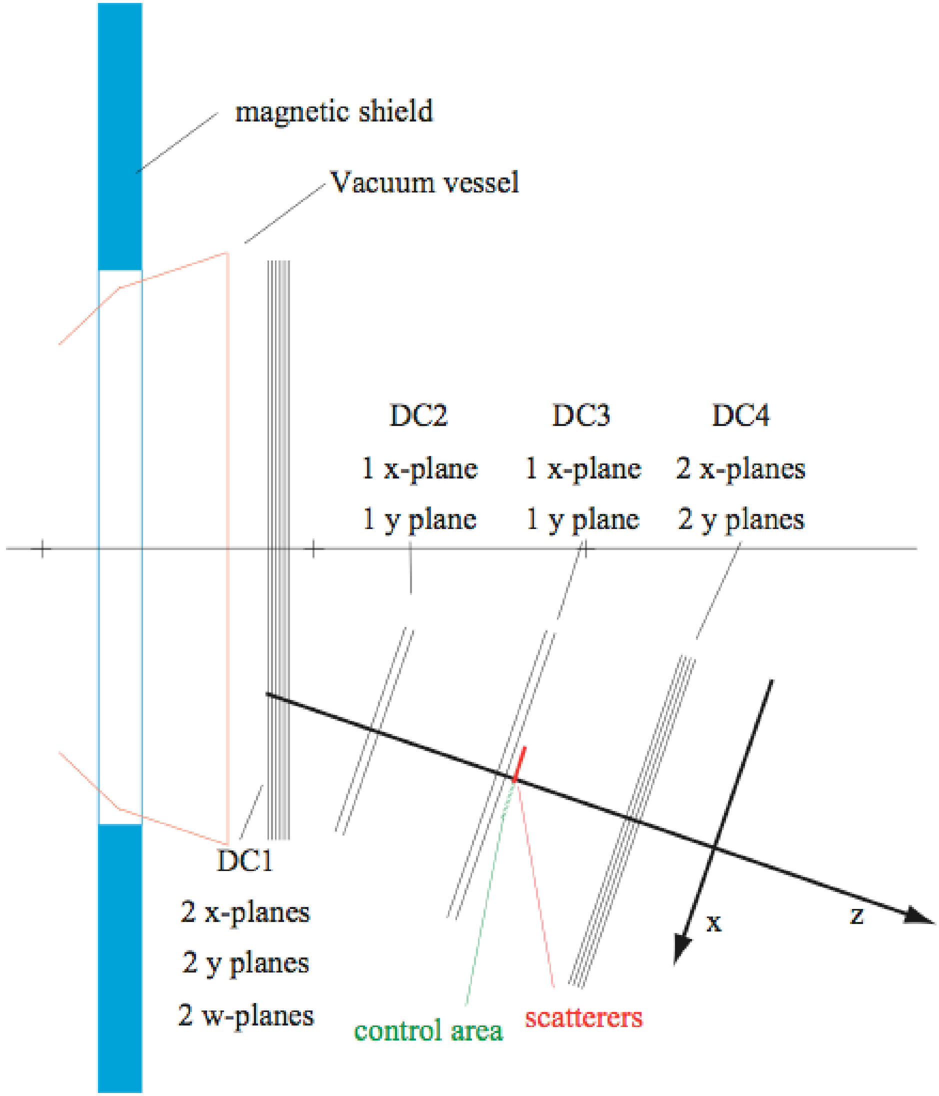
Improved total stat. error on P_{br}: ± 0.012 ($\pm$ 2.6%)

Dedicated measurement on Multiple scattering

The drift chambers were used to measure multiple scattering in the most relevant materials:

- •Ni-target, 98 mm
- •MSGC, 1 plane
- •SFD-x
- •SFD-w
- •IH, 1 plane
- •Al-window

Accuracy of measurement: ca. 1%



Results:

- •Multiple scattering on pure materials (Ni, Al) is correctly described by standard GEANT Moliere treatment (1% accuracy).
- •Composite materials (MSGC, SFD) had to be corrected in thickness by +10 to +15 percent.

Improvements on Multiple scattering

Published systematic error on P_{br}: + 0.006(+1.3%) - 0.013(-2.9%)

First error from 1% uncertainty in mult. scattering in general
Second error due to assumed systematics, disappears

Improvement on syst. error from mult. scatt. on P_{br}: ± 0.006 (± 1.3%)

Improvements on CC background

Improved generators (better laboratory momentum distributions, improved acceptance simulations etc.) eliminate systematics from fit-range.

Published error on P_{br}: ± 0.007(±1.6%)

New estimate: ± 0.003 (± 0.7%)

Heavy particle admixtures

K^+K^- or pp_{bar} pairs are misidentified as $\pi^+\pi^-$ pairs. Due to their lower speed, they have a more pronounced Coulomb correlation than pion pairs and therefore may disturb the determination of CC-background. While in transverse direction the enhancement is of the order of a factor 3.5, in the longitudinal direction it is, due to the different boost, about a factor 13.5 higher (K^+K^-) than for pion pairs. The sensitivity on these admixtures is therefore much higher in Q_L than in Q_T.

The error estimate from the publication was based on a fit in Q_L only.

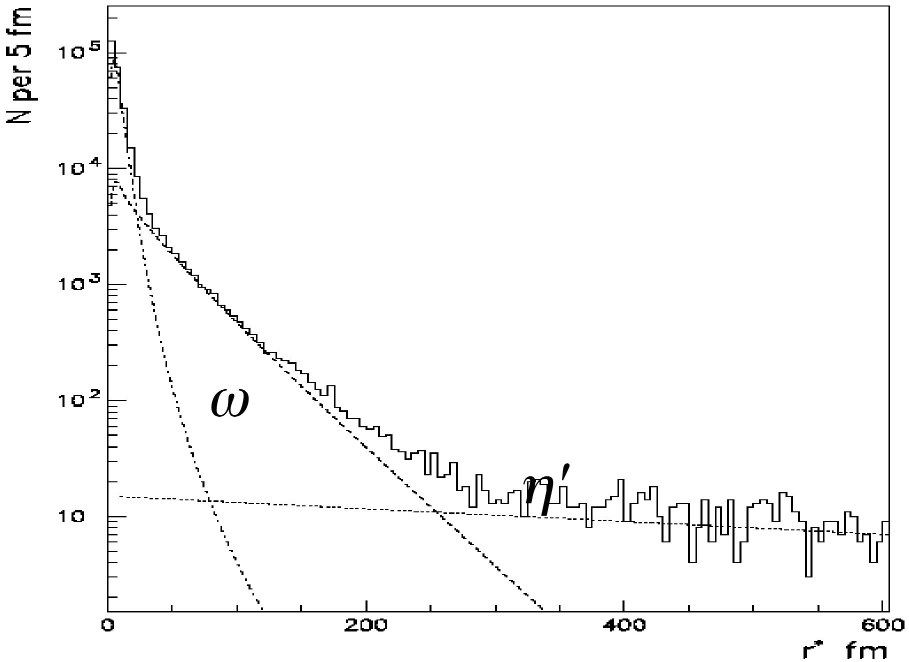
Fitting Q-distribution reduces sensitivity substantially.

Published error on P_{br}: + 0.000(+0.0%) - 0.023(-5.1%)

Improved error from K^+K^-, pp_{bar} on P_{br}: + 0.000(+0.0%) -0.005(-1.3%)

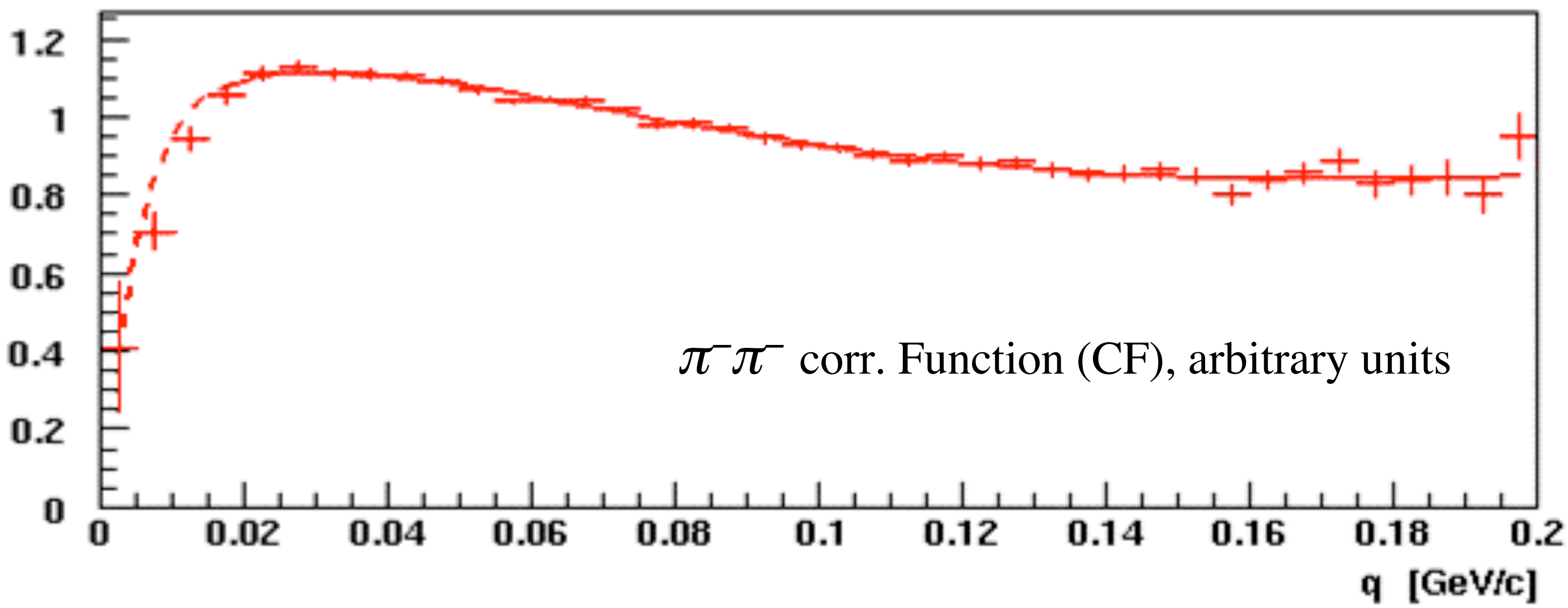
Finite-size effects

characteristic scale |*a*| = 387 *fm* (Bohr radius of *pp* system)
average value of radius of production volume $r^* \sim 10$ *fm*
range of $\omega \sim 30$ *fm*
range of $\eta' \sim 900$ *fm*
critical region of $r^* \sim |a|$ is formed by ω and η' pairs



UrQMD simulation *pNi* 24 GeV:
- ~15% ω pairs
- < 1% η' pairs

$\pi^-\pi^-$ correlation function from DIRAC



Simulation (UrQMD, $N_\omega(\pi^-\pi^-) = 19.2\%$) fits
the DIRAC $\pi^-\pi^-$ CF very well

Finite size correction

Need better low-Q $\pi^-\pi^-$ data

Published error on P_{br}: + 0.000(+0.0%) - 0.017(-3.8%)

Error unchanged: + 0.000(+0.0%) - 0.017(-3.8%)

Summary precision on P_{br}

	update		Old	
P_{br}-Statistics	±2.6%		± 5.1%	
P_{br}-Systematics	+1.5%	-4.2%	+2.1%	-7.2%
P_{br}-Total	**+3.0%**	**-5.2%**	**+5.5%**	**-8.7%**
$\vert a_0 - a_2 \vert_{stat}$	±3.5%			
$\vert a_0 - a_2 \vert_{tot}$	**+7.4%**	**-4.2%**	**+12.5%**	**-7.4%**

Further improvements are expected due to fit-procedures and experimental assessment of finite size corrections

Conclusion and outlook

DIRAC has essentially achieved the goal from the proposal

Systematic errors have been studied and significant improvements were obtained

Statistical errors have improved due to better reconstruction and more analyzed data

Open problems are connected with the understanding of

1. **Finite size correction**
2. **Heavy particle admixtures**

Outlook

Finite size corrections need better measurements on $\pi^-\pi^-$ correlation function at small Q.

This will be done in coming runs for DIRACII

Heavy particle admixtures will be measured in DIRACII.

DIRACII will improve statistics and systematics to the level indicated on page 3.